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Direct Determination of the Thickness of Stratospheric Layers From Single-Channel Satellite Radiance Measurements

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ABSTRACT—The direct use of measured radiances for determining the thickness of stratospheric layers is investigated. We hypothesize that the equivalent blackbody temperature, weighted according to the transmittance weighting functions for the stratospheric channels of the satellite infrared spectrometers and the selective chopper radiometer, gives a good approximation of the geometric mean temperature of *some* layer within the transmittance (τ_ν) domain $0<\tau_\nu<1$. A priori, it is shown that under certain conditions this is not a good assumption. However, it is of interest to determine for what atmospheric layers acceptably small error in the mean temperature, and therefore in the thickness, would be incurred. Layers based at 100–10 mb, with upper boundaries at 10–0.5 mb, are investigated using a carefully selected family of stratospheric temperature profiles and computed radiances. On the basis of physical reasoning, a high correlation of thickness with radiance is anticipated for deep layers, such as the 100- to 2-mb layer (from about 15 to 43 km), that emit a substantial part of the infrared energy reaching a satellite radiometer in a particular channel. Empirical regression curves relating thickness and radiance are developed and are compared with "blackbody" curves obtained by substituting the blackbody temperature in the hydrostatic equation. Maximum thickness-radiance correlation is found, for each infrared channel, for the layer having the best agreement of empirical and blackbody curves. For these layers, the data from a single radiation channel accounts for a reduction of variance by up to 97 percent. The utility of thickness data based on actual radiances is demonstrated through independent testing and with a sample 2-mb map constructed by adding thicknesses based on measured radiances to the observed 100-mb height field.

1. INTRODUCTION

Radiation measurements by the satellite infrared spectrometer (SIRS) instruments (Smith et al. 1972) on the Nimbus 3 and 4 satellites have provided an important new data source for investigating the atmospheric structure. By inverse solution of the radiative transfer equation, vertical temperature profiles have been obtained that generally agree closely with radiosonde measurements up to the middle stratosphere (about 30 mb or 25 km). The bulk of the radiation received by the SIRS instruments comes from thick atmospheric layers centered at levels below 30 km. Because of the reduction in the SIRS transmittance weighting functions above this level (fig. 1), the derivation of the temperature of the upper stratosphere is quite problematical (Quiroz 1971). For determining temperature profiles above 30 km, statistical techniques incorporating radiance information have been especially useful (Gelman et al. 1972). Moreover, the use of radiation data from the selective chopper radiometer (SCR) instrument flown in Nimbus 4, which has a weighting function peaking near the 2-mb level (Barnett et al. 1972), and the planned application of limb radiance techniques (Gille and House 1971) in 1974 offer considerable promise for reliable remote soundings extending above 30 mb.

Whether or not detailed vertical temperature soundings are obtained using complex retrieval procedures, it is still possible to extract much useful information directly from the measured radiances. The radiance data indeed have already proved extremely useful for monitoring events in the upper stratosphere during the past 3 yr (Fritz 1970, Quiroz 1971, Fritz and McInturff 1972). In this report, we will be concerned with using radiances to specify the thickness of deep stratospheric layers; for example, the 100- to 2-mb layer. By adding the thickness to the observed height field for the lower boundary, one may then construct constant-pressure maps at very high altitudes. These maps can serve either as end products for use in reentry calculations and other aerospace applications or as first-guess fields for improved maps incorporating other information.

The thickness of layers extending up to the 10-mb level has been estimated by Nicholas (1970), using Nimbus 2 medium resolution infrared (MRIR) data. The radiation data required a cloud correction and, when used alone, accounted for a 50-percent reduction of variance, at most. Because of differences in the weighting functions, we expected that the SIRS and SCR data would prove more suitable for specifying stratospheric thickness.

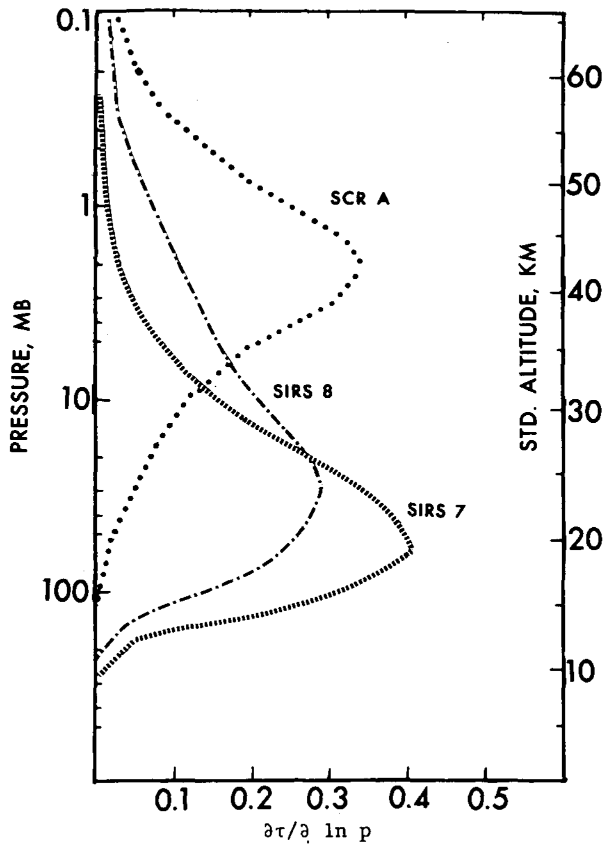

FIGURE 1.—Transmittance weighting functions for SCR channel A and SIRS B channels 8 (669 cm^{-1}) and 7 (680 cm^{-1}).

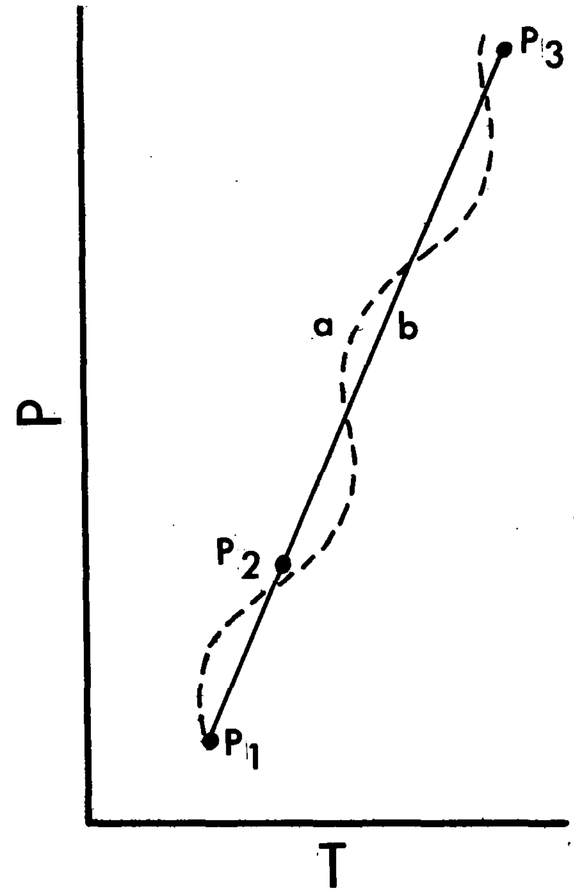

FIGURE 2.—Hypothetical temperature profiles intended to illustrate expected influence of layer thickness on correlation between radiance and thickness.

2. PHYSICAL BASIS

In the absence of observational error, the measured radiance, I, at a specific wave number, ν, corresponds to a temperature, through the Planck equation, that is the temperature of the atmospheric layer in the domain $0<\tau<1$, weighted according to the appropriate transmittance weighting function, $\partial\tau/\partial \ln p$ (fig. 1). This temperature is generally different from the geometric mean temperature of the layer, which is based on equal weighting throughout the layer. For this research, the hypothesis was first made that the blackbody temperature, T^*, given by the radiance measured in a specific channel, gives a good approximation to the geometric mean temperature (or, through the hydrostatic equation, to the thickness) of *some* layer within the positive domain of the weighting function; that is,

$$z_2-z_1\approx\frac{RT_\nu^*}{g}\ln\frac{p_1}{p_2}, \tag{1}$$

where, from the Planck equation, $T_\nu^*=f(I_\nu)$. We then ask, what is this layer and how good is the approximation?

A priori, we may anticipate significant errors. Consider SIRS channel 8. Figure 1 shows that the overall weight for the 100- to 10-mb layer (approx. 15–30 km) is roughly twice as great as for the layer 10–1 mb (approx. 30–45 km). Suppose that in case A the upper layer is warmed to $T+\Delta T$ while the lower layer remains at T. Suppose that in case B the upper layer remains at T while the lower layer is warmed to $T+\Delta T$. It is obvious then that, because of the different weights in the two layers, the radiance change will be different in cases A and B, but the thickness change will be identical. Thus, a priori, we know that errors will result from using eq (1), but it is possible that for real atmospheric conditions these errors may be acceptably small.

What layers should be investigated? Physical reasoning suggests that the radiance should be correlated best with thick layers spanning a substantial part of the domain of the weighting function. The detailed transmittance data for SIRS channel 8 indicate that the great bulk of the emitted infrared energy should come from a deep layer spanning most of the stratosphere. For example, about 80 percent of the energy is from the 100- to 2-mb layer (about 15–43 km). If large temperature changes occur at much higher or lower altitudes, they significantly affect the thickness of the layer encompassed; but, because these temperature changes have small weighting, they affect the integrated radiance very little. Thus, for layers much deeper than, say, the 100- to 2-mb layer, the correlation of thickness with radiance should decrease.

On the other hand, much thinner layers can also be expected to show a reduced correlation. The simple

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temperature profiles in figure 2 illustrate why. Profiles a and b give roughly the same integral radiance; that is,

$$I_a \approx I_b \approx \sum_{p_0}^{p=0} B_\nu[T(p)]\Delta\tau(p)$$

where B is the Planck function. They also give essentially the same mean temperature, or thickness, for the deep layer from p_1 to p_3. However, consider the shallow sublayer, p_1–p_2. Here, the different mean temperatures give different thicknesses; yet, in any one channel, a satellite radiometer would measure nearly the same radiance in both cases. These considerations, therefore, led us to investigate layers of substantial thickness based at 100–10 mb with upper surfaces at 10–0.5 mb.

3. RESULTS BASED ON COMPUTED RADIANCES

To determine the best relationships of radiance with layer thickness, we assembled a sample of 75 carefully selected, stratospheric temperature profiles. This set, formed from combined radiosonde and rocketsonde data, includes not only "typical" profiles possessing the basic structures of the standard atmosphere (COESA 1966) but also numerous profiles with anomalous structures, such as are observed before and during stratospheric warmings (Quiroz 1971). Table 1 gives the distribution of soundings. We deliberately emphasized high-latitude, wintertime conditions over a wide range of longitude since it was intended that any predictors to be developed should be fully useful for specifying wintertime synoptic variability. The small number of low-latitude soundings would suggest unbalanced sampling. However, the extremes of temperature and pressure in the middle and upper stratosphere do not occur in low latitudes; they occur within the polar vortex or in connection with high-latitude stratospheric warmings. Thus, the sample embraces the range of values to be expected in the Northern Hemisphere over a period of several years.

TABLE 1.—*Distribution of soundings (mainly 1966–70)*

	October-March	April-September	Total
High latitudes (>50°)	56	9	65
Low latitudes (<50°)	9	1	10

For each temperature profile, $T(p)$, the heights of the 100-, 50-, 30-, 10-, 5-, 2-, 1-, and 0.5-mb pressure surfaces and the thicknesses of all layers with bases at 100, 50, 30, 10, or 5 mb were determined. Also, for each profile, the SIRS channels 8 and 7 and SCR channels A, B, and C radiances were computed, using the appropriate weighting functions. The weighting properties of SCR channels B and C are similar to those of SIRS 8 and 7, respectively, offering a desirable redundancy in the case of failure of one or the other instrument.

TABLE 2.—*Correlation coefficients,* r, *standard errors of estimate,* S_E *(m), and ratio of standard error to standard deviation,* S_Y *(m), of predictand,* Δz*; curvilinear regression*

Δz(mb)	Predictor channels (7) r	(7) S_E	(7) S_E/S_Y	(8) r	(8) S_E	(8) S_E/S_Y	(A) r	(A) S_E	(A) S_E/S_Y	(B)† r	(C)‡ r	S_Y
100–10	0.952	217	0.34	0.779	447	0.63	0.325	674	0.94	0.739	0.958	713
100–5	.967	247	.26*	.901	417	.43	.524	819	.85	.886	.975	962
100–2	.903	583	.43	.985	233	.17*	.764	874	.64	.984	.904	1355
100–1	.823	956	.57	.982	313	.19	.869	833	.49	.985	.820	1681
100–0.5	.769	1257	.64	.963	527	.27	.921	764	.39	.959	.758	1966
50–10	.929	212	.37	.820	329	.57	.412	525	.91	.930	.941	576
50–5	.924	325	.38	.923	327	.38	.599	681	.80	.928	.937	850
50–2	.843	688	.54	.979	262	.21	.812	746	.58	.843	.847	1279
50–1	.759	1060	.65	.963	444	.27	.899	715	.44	.757	.758	1629
50–0.5	.710	1354	.70	.941	649	.34	.944	637	.33	.700	.700	1924
30–10	.876	216	.48	.783	279	.62	.389	413	.92	.879	.887	448
30–5	.886	336	.46	.913	296	.41	.616	572	.79	.892	.899	726
30–2	.796	709	.60	.962	319	.27	.833	650	.55	.798	.800	1175
30–1	.716	1069	.70	.945	503	.33	.916	615	.40	.713	.713	1532
30–0.5	.668	1365	.74	.921	717	.39	.956	538	.29	.656	.656	1836
10–5	.694	261	.72	.863	183	.51	.753	238	.66	.901	.705	362
10–2	.620	691	.33	.885	410	.47	.913	359	.41	.916	.617	881
10–1	.554	1066	.83	.856	662	.52	.960	360	.28	.882	.545	1280
10–0.5	.524	1369	.85	.834	887	.55	.984	286	.18*	.846	.505	1606

*A best result
†Compare with SIRS channel (8)
‡Compare with SIRS channel (7)

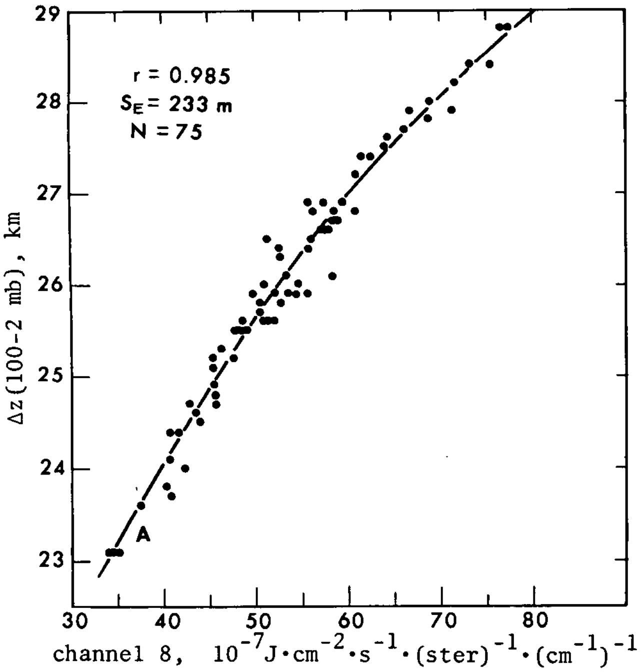

FIGURE 3.—Relationship between SIRS channel 8 radiance and thickness of layer 100–2 mb, based on developmental sample of 75 soundings.

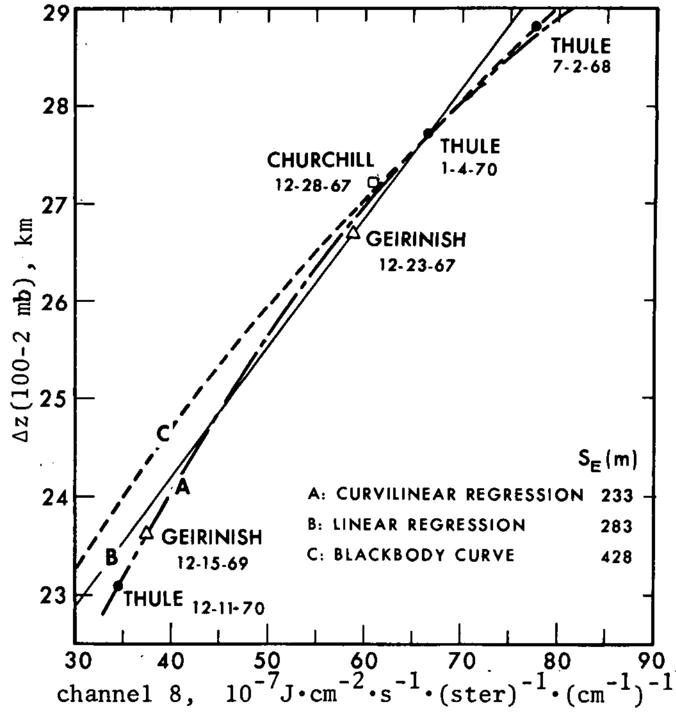

FIGURE 4.—Curvilinear relationship (curve A, from fig. 3) compared with linear and blackbody relationships, along with selected data for Thule, Greenland (77°N, 69°W), Ft. Churchill, Canada (59°N, 94°W), and West Geirinish, Scotland (57°N, 7°W).

Observed layer thickness versus radiance was then plotted to isolate the most promising empirical relationships and to determine the usefulness of the blackbody relationship [eq (1)]. Empirical regression equations were generated by computer as follows: (1) linear equations of the form $\Delta z=a+bI_\nu$; (2) second-degree equations of the form $\Delta z=a+b_1I_\nu+b_2I_\nu^2$, involving the same radiation channel in the first- and second-degree terms; and (3) linear equations involving more than one radiation channel. The equations involving multiple channels were obtained by Woolf (1972), to whom we are also grateful for the radiance calculations.

Table 2 shows data from the computer printout illustrating some of our principal findings. The results shown pertain to the second-degree equations based on the entire data sample ($N=75$); data were also computed for the winter high-latitude subsample ($N=56$) identified in table 1.

Discussion

Table 2 essentially confirms that there is a "best" layer for which thickness can be determined using a single radiation channel. For channels 7, 8, and A, these are the 100- to 5-mb, 100- to 2-mb, and 10- to 0.5-mb layers, respectively. The relationships indicated involved correlation coefficients of 0.96–0.99, or a reduction of variance by as much as 97 percent and standard errors in thickness of 200–300 m. While such standard errors might appear large to tropospheric meteorologists, they constitute only a small fraction of the overall variability in the stratosphere, as evidenced by the ratios of standard error to the standard deviation of the predictand.

There are well-defined maxima in the correlation arrays. In the case of SCR channel A, a maximum is found at the upper limit of the data; that is, for the 10- to 0.5-mb layer. It is possible that the true maximum is for an upper boundary at a slightly higher altitude; however, the correlation should decrease above that level because of the strong upward reduction in the SCR channel A weighting function (fig. 1). Further computation was not carried out because the available rocketsonde data become increasingly unreliable at the higher altitudes.

The relationship between radiance and thickness for the 100- to 2-mb layer is further illustrated in figures 3 and 4. Figure 3 is a plot of observed thickness versus computed radiance from channel 8; curve A in each figure represents the second-degree polynomial regression relationship. Figure 4 shows, in addition, a linear fit, curve B, and a blackbody curve, C, obtained from eq (1). The root-mean-square (rms) error in specifying thickness from the blackbody curve is twice as great as from curve A, which gives the best fit to the data.

We now return to the hypothesis, stated earlier, that there is some layer for which the blackbody temperature gives a good approximation of the layer thickness. For SIRS channel 8 and the 100- to 2-mb layer, this hypothesis is borne out if one considers an rms error of 428 m acceptable. Figure 5 provides additional information on this question. Proceeding vertically through the figure, one observes the blackbody curve "passing" through the empirical curve. The best agreement of a pair of curves is for the layers 100–2 and 100–1 mb, where the highest correlations of radiance with observed thickness are also

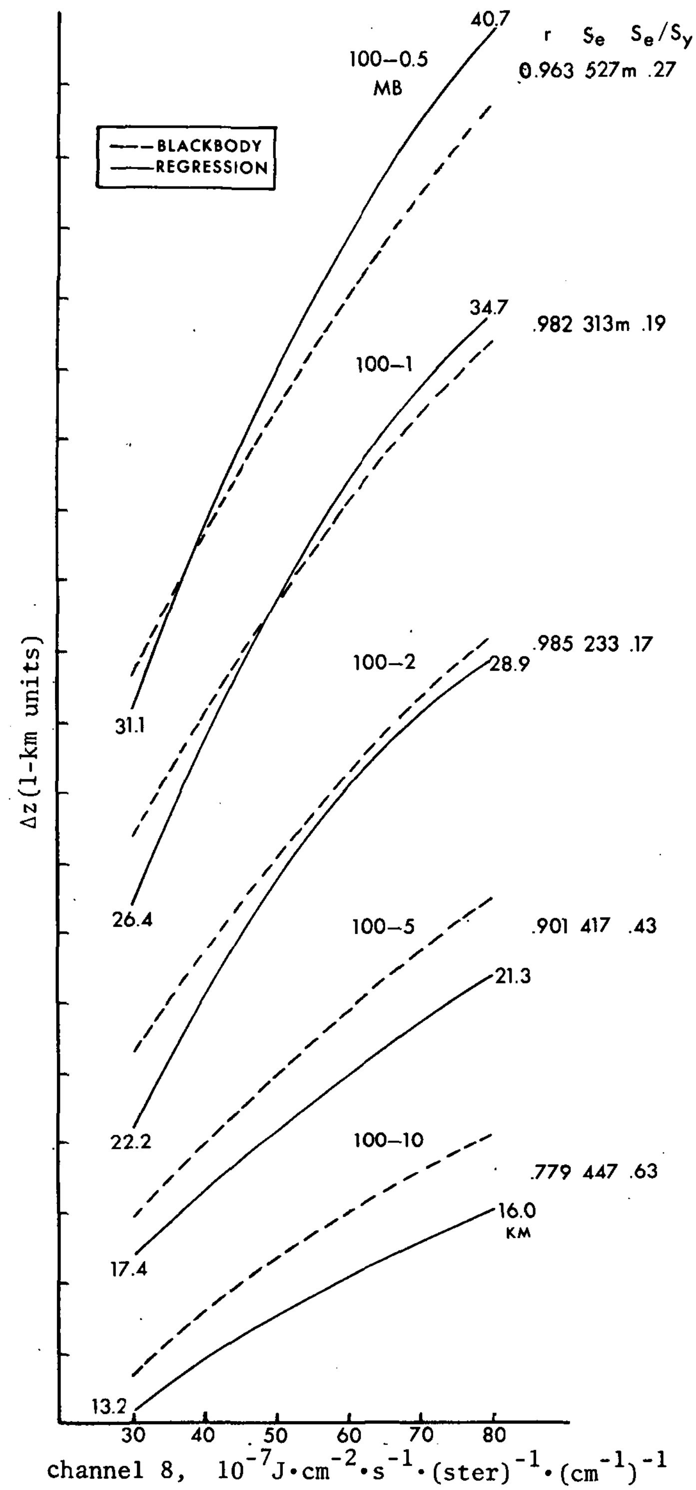

FIGURE 5.—Comparison of blackbody curve (derived from the Planck and hydrostatic equations) with empirical regression curve, for specified layers. Ordinate values for each pair of curves may be determined from regression thickness values at radiance values of 30 and 80×10^{-7} J·cm^{-2}·s^{-1}·(ster)$^{-1}$·(cm^{-1})$^{-1}$. Regression statistics are given at right.

found (0.985, 0.982). The very best layer probably lies at about 100–1.5 or about 80–1.5 mb (a determination not given because of the resolution in our input data). For such a layer, the blackbody and empirical curves should give nearly identical results.

Similar figures (not shown) with lower boundaries fixed at 50, 30, or 10 mb also show a convergence of the blackbody and empirical curves for those layers associated with a correlation maximum (table 2). These are, however, thinner layers; and, as was anticipated on physical grounds, lower correlations are found than for the thick layers, 100–2 or 100–1 mb. The same essential behavior was noted in plots of blackbody and empirical curves involving the use of SIRS channel 7 (best agreement for layer at 100–5 mb) and SCR channel A (best agreement at 10–0.5 mb). The hypothesis is thus confirmed. Moreover, the blackbody curve gives the best approximation of thickness for the layer involving the highest empirical correlation of radiance and thickness.

The final choice of curve depends on the intended application. For example, for constructing 2-mb maps, the curvilinear regression curve would be preferred because it gives the lowest standard error in the 100–2 mb thickness (fig. 4). The use of any of these curves is straightforward since, with the aid of a conversion table, analyzed radiance isolines on a map may simply be relabeled as thickness lines.

Further Statistical Considerations

Questions naturally arise regarding (1) the representativeness of the sample and (2) the possible use of multiple correlation involving several physical parameters (e.g., more than one radiation channel) (Smith et al. 1970). As mentioned earlier, correlations were also obtained based on winter, high-latitude conditions only ($N=56$). For the layers listed in table 2, the correlations were found to change very little, decreasing by 0.5–2.0 percent for those cases in which the initial correlations based on the total sample exceeded 0.90. The standard errors also changed very little. Thus, the convenience of using a single set of regression equations covering all conditions probably compensates for the slight advantage that might accrue from stratifying the sample.

Figure 4 illustrates the efficiency of the curvilinear regression equation ($N=75$) in stratospheric warming situations. The maximum value of thickness and radiance depicted at Thule, Greenland, on July 2, 1968, represents a typical high-latitude summer extreme condition. The low values in the lower part of the diagram are midwinter nonwarming cases. The three remaining data points, however, are winter warming cases and are very well predicted by the regression curve.

Thus far, the discussion has concerned relationships with a single type of measurement, such as channel 8. Regression equations involving more than one radiation channel and/or predictor based on radiosonde data, such as the height of the lower boundary surface, would also have merit. Calculations showed that slight improvements in the correlations are possible, but it is doubtful that such multiple correlation is truly advantageous in those cases where the correlations with a single radiation channel are already very high ($\geq$0.95). In such cases, the use of a single channel is especially attractive because of (1) its

TABLE 3.—*Observed minus predicted layer thickness (m)*

Layer	Predictor channel	Sample	S_E	S_E/S_Y	Mean difference	Mean absolute difference
100–5 mb	7	Developmental	247	0. 26	0	200
		Independent	289	. 34	−20	230
100–2 mb	8	Developmental	233	. 17	0	180
		Independent	301	. 24	−22	260
10–0.5 mb	A	Developmental	286	. 18	0	220
		Independent	706	. 94	−581	595
		Indep. (adj.)*	385	. 55	0	304

*Adjusted for bias (−581 m), as discussed in text

Note: Range and standard deviation of observed thicknesses (m) in developmental and independent samples are:
Δz(100–5 mb): 4300, 962 (dev.); 4300, 844 (ind.)
Δz(100–2 mb): 5700, 1355 (dev.); 5700, 1280 (ind.)
Δz(10–0.5 mb): 6400, 1606 (dev.); 4100, 754 (ind.)

simplicity, (2) the facility for readily converting analyzed radiance maps to thickness maps, (3) the ability to detect data irregularities, sometimes of instrumental origin, with the aid of the map analyses, (4) the ability to reconstruct or completely depict synoptic features in the radiance fields where measured data are sparse, and (5) the clear physical basis for the relationships.

Regression with more than one channel may be desirable in those cases involving simple correlations in the range 0.60–0.95. Provided the channels used are not themselves strongly correlated, a significant improvement is expected in these cases. For the general solution of the thickness of arbitrary layers, results based on detailed temperature profiles retrieved according to recent developmental work (Gelman et al. 1972, Smith et al. 1972, Barnett et al. 1972) should also be investigated. It is noteworthy, however, that, if one plots the correlation data of table 2 as a function of the upper boundary pressure, correlations exceeding 0.95 are found throughout the levels from 10 to 0.5 mb. Thus, data from a single radiation channel, appropriately chosen, can provide useful thickness information for layers with upper boundaries in the upper stratosphere or lower mesosphere.

The use of the lower boundary surface, for example z(100 mb), as an additional predictor does not appear vital in these results, in contrast to the findings of Nicholas (1970). The layers he was concerned with, reaching no higher than the 10-mb level, do exhibit a high correlation with the height of the lower surface. The correlation of Δz(100–2 mb) with z(100 mb) is only about 0.3. We believe that the most useful way of incorporating information on the lower surface is, as indicated earlier, by adding the specified thicknesses to the actual lower boundary height field on any given day.

4. INDEPENDENT TESTING

Although excellent results were obtained using *computed* radiances, it is of special interest to apply the regression equations under operational conditions. An independent test was, therefore, carried out using values of radiances measured by Nimbus 3 and 4 satellites. The independent sample ($N=75$, December 1969–January 1972) has properties similar to those of the dependent sample with a preponderance of high-latitude winter observations, several of which were taken during a warming episode.

From map-analyzed SIRS channel 7 and 8 and SCR channel A radiances, the thicknesses of the 100- to 5-, 100- to 2-, and 10- to 0.5-mb layers were specified using the curvilinear regression equations described in the preceding section. These were then compared with radiosonde-rocketsonde observed thicknesses. Statistical results are given in table 3.

We expected the standard error to increase because of the use of real radiances in the independent testing. The SIRS independent results are in very good agreement, considering the possibility for errors in the measured radiances and in the rocketsonde data, as well as error associated with the analysis. For the 100- to 5- and 100- to 2-mb layers, there is an increase of 40–70 m in S_E, corresponding to a radiance difference of roughly 0.5×10^{-7}J, although a part of this increase is undoubtedly due to the different sampling.

In the case of the SCR channel A results, a bias amounting to 581m (table 3) was discovered. (See also Miller and Finger 1972.) Since no comparable bias was evident in the results for SIRS, this finding suggests (1) a 5×10^{-7} J·cm^{-2}·s^{-1}·(ster)$^{-1}$·(cm^{-1})$^{-1}$ calibration error in the measured SCR radiances or (2) error in the transmittances. The British experimenters have suggested (Houghton 1972) that the bias lies in the transmittance data used,[1] and investigation of this problem has been initiated. For interim application of the SCR results, however, an adjustment to compensate for this bias can be made. With such an adjustment, the standard error is reduced by one-half (table 3). As with the SIRS data, there is a reasonable increase in the resulting standard error when compared to the value (286 m) for the developmental sample. The percentage increase is slightly greater

[1] The transmittances were provided by C. D. Rodgers, Clarendon Laboratory, Oxford, England, in November 1971.

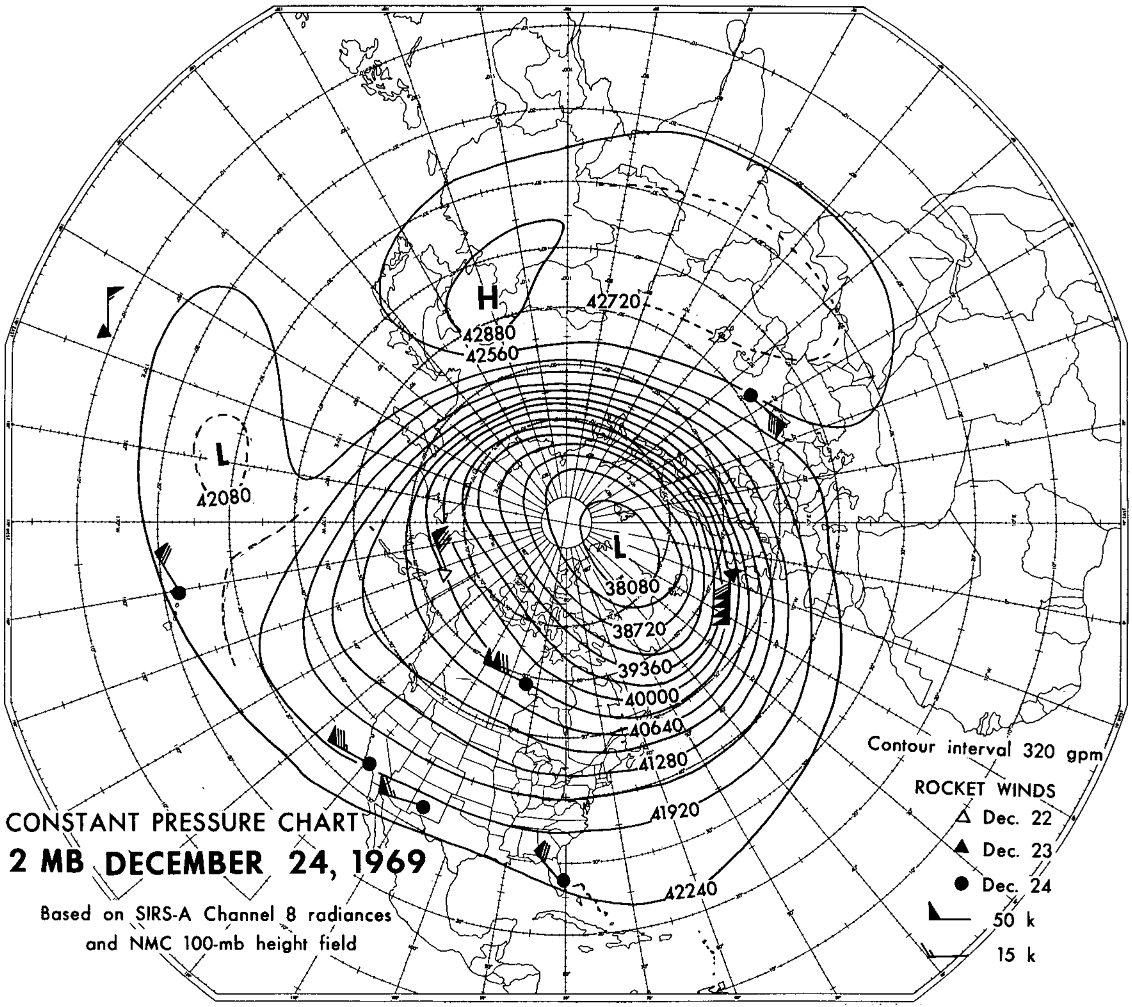

FIGURE 6.—Sample 2-mb chart constructed from SIRS channel 8 radiance analysis. The use of SIRS A, rather than SIRS B, radiances (first available in 1970) should introduce an error of about 100 m in the 2-mb height field as a result of a slight difference in the weighting functions.

than for SIRS, suggesting more noise in the SCR radiances. The observed SCR radiance data available to us are for November 1971–January 1972 and may not constitute an adequate sample for testing. Thus, these results must be regarded as preliminary.

In view of the excellent results thus far obtained, we decided to begin an experimental series of high-level maps based on the satellite-measured radiances. A sample 2-mb map for Dec. 24, 1969, is shown in figure 6.[2] This map was constructed by simply relabeling the SIRS channel 8 radiance isolines and adding the thicknesses to the 100-mb National Meteorological Center map for that day. No other information was used. Observed rocket wind data were entered subsequently. It is evident that there is good agreement between the observed winds and the geostrophic winds given by the map; moreover, comparison of the map with a 2-mb chart previously constructed using all available rocket wind and thermodynamic data shows good agreement in all important respects. The situation depicted occurred during the development of a major stratospheric warming and is marked by an intense pressure gradient between the polar vortex and the Asian anticyclone.

[2] "Real-time" map analyses at three levels, 5, 2, and 0.4 mb, were initiated in January 1972.

5. CONCLUSIONS

For the radiation channels examined, the hypothesis that the equivalent blackbody temperature gives a good approximation of the thickness of some layer in the appropriate transmittance domain is confirmed by observational evidence. For SIRS channels 7 and 8 and SCR channel A, the best approximation is found for the layers at approximately 100–5, 100–2, and 10–0.5 mb, respectively. For such layers, there was close agreement between the blackbody and empirical curves relating radiance and thickness. The empirical regression equations indicated a reduction in variance up to 97 percent due to the use of radiation data from a single channel. The ratio of standard error of estimate to standard deviation of the predictand is close to 0.2, based on simulated radiances.

Real, map-analyzed radiances may be used, as was shown by independent testing. Because of instrumental and analysis error, the standard error is slightly greater when real SIRS radiances are used. Independent testing revealed a bias in the SCR specifications, probably related to error in the transmittances, suggesting the need for further testing and for investigation of the transmittance data. In the interim, adjustment for the bias may be made to give a smaller standard error. The utility of thickness data converted directly from analyzed radiances was illustrated by a sample 2-mb map constructed by adding radiance-derived thicknesses to the observed 100-mb height field.

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